Full-Motion Aircraft Simulator Enhancements to Improve Cockpit Response to Pavement Roughness

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ABSTRACT

As a preliminary to a project to measure pilot's subjective response to vertical cockpit vibrations in ground maneuvers, the software of the Boeing 737 full-motion simulator located at the FAA Mike Monroney Aeronautical Center in Oklahoma City has been modified to enhance the representation of cockpit response to pavement roughness. Modifications made to the software include the ability to load longitudinal elevation profiles measured on airport pavements, suppression of the generic roughness simulation models, and the addition of flexible body modes to the flight system dynamic simulation model. The modifications are described, together with the procedure used to transfer the computed vertical cockpit accelerations to the motion system. Cockpit accelerations computed in response to a number of test profiles are compared with accelerations measured with a physical accelerometer positioned below the pilot's seat in the simulator cockpit. Comments made by two test pilots regarding the fidelity of the cockpit acceleration responses during taxiing, takeoff, and landing are reported. The pilots considered the responses to feel realistic except for the representation of background roughness, induced tire noise and the absence of responses to passing over centerline lights and concrete pavement joints.

INTRODUCTION

Airport pavement standards ensure that surface roughness is within acceptable limits for new construction. These standards include maximum variances along both axes of new runway construction. However, once the construction is complete the FAA does not have a reliable method for determining when an airport pavement becomes "too rough" due to deterioration of the pavement structure and surface characteristics. This lack of reliable indicator indexes means that maintenance activities related to excessive roughness cannot be planned and executed as efficiently as might be possible.

Several methods have been developed to measure and report the physical variations of pavement roughness. These methods all require the measurement of longitudinal elevation profiles of runways and taxiways, and include the Boeing Bump, Gear Acceleration, International Roughness Index (IRI), Ride Index (RI), Bandpass Filters, Power Spectral Density, etc., but suitable criteria for use of these indexes to report airport pavement roughness condition have not so far been established. The most common method in use is to identify possible pavement defects from pilot reports of excessive roughness, perhaps coupled with further investigation of defects by predicting airplane vertical accelerations through dynamic simulation of the airplane's motion.

The approach used to evaluate and rank the roughness of highway pavements that has been in use for many years is to conduct a study of the subjective evaluation of the roughness of selected highway sections by drivers and passengers riding in normal sedan cars as the cars are driven along the sections. At the same time, longitudinal profiles of the pavement sections are measured and reduced to summary index values, such as IRI or RI. A correlation is then performed relating the subjective ratings to the index values. Then, in routine roughness evaluation test programs, the profiles of the pavements to be evaluated are measured and index values computed. The roughness of the pavements is then given a ranking based on the correlation previously determined between the subjective ratings and the index values (see reference 1 for more information). It is felt that a similar approach might be applicable to the rating of airport pavement roughness, with the subjective ratings being determined by pilots and copilots riding in the cockpits of airplanes during ground maneuvers. However, severe operational constraints are placed on pilots during ground operations and at low altitudes during flight, and conducting a subjective rating study during airplane operations is not a practical option. Full-motion airplane simulators are widely used and are highly sophisticated, and conducting subjective rating studies in a simulator is a viable alternative to at least determine the feasibility of using transformed pilot ratings to evaluate the roughness of airport pavements. As a preliminary to a project to measure pilot's subjective response to vertical cockpit vibrations in ground maneuvers, the software of a Boeing 737-800 full-motion simulator owned and operated by the FAA, and located at the Mike Monroney Aeronautical Center in Oklahoma City, has been modified to enhance the representation of cockpit response to pavement roughness.

FAA B737-800 FLIGHT SIMULATOR

The B737-800 CAE full flight simulator is an FAA certified Level D flight training device, providing a six-degree of freedom motion system, high resolution visual display and sound system. The simulated cockpit is designed to provide an accurate functional representation of the actual aircraft cockpit. The aircraft system dynamics are modeled in real time. Simulated real-world visual environments provide a high level of detail for selected airports.

The main flight simulator software runs on a host computer with a maximum iteration rate of 60 Hz. The motion and visual systems exist as separate hardware components with Ethernet used for communication with the host computer.

Flight Model

The flight model software simulates the dynamics of systems associated with the aircraft's movement in flight and on the ground. The flight model assumes a rigid aircraft structure. Body and wing flexing effects are not explicitly modeled in the standard flight model but are injected into the simulator motion where needed for realism. The flight model outputs aircraft linear and rotational velocities and accelerations to the simulator visual and motion systems. The flight model software is divided into the following modules:

- Atmosphere
- Aerodynamics
- Equations of Motion
- Ground
- Weight
- Thrust

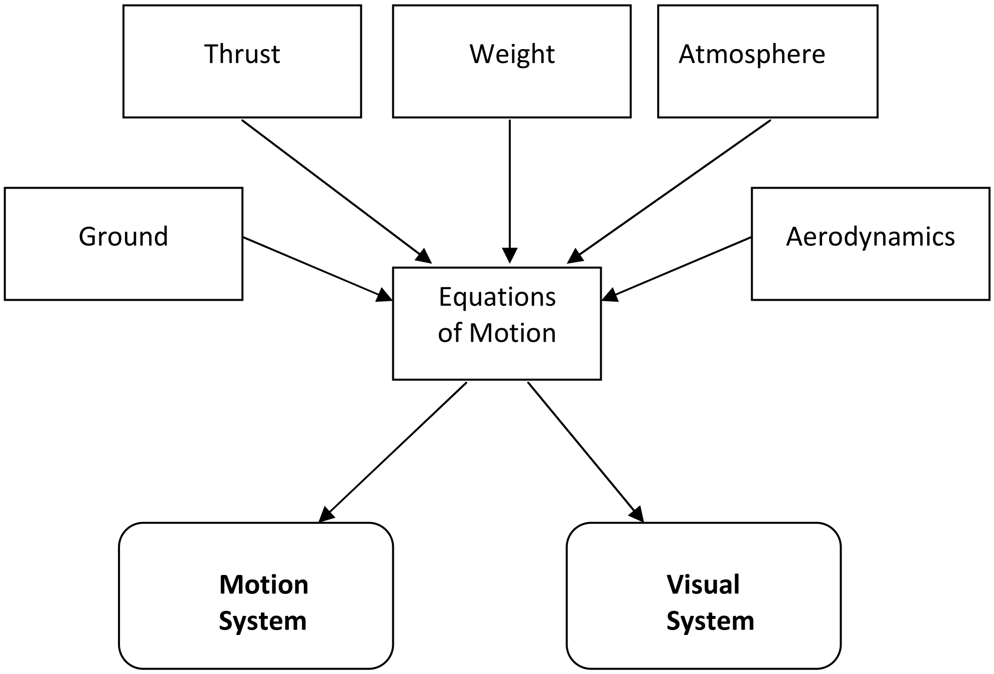

Figure 1. Simulator flight model diagram

The ground module computes ground interaction with the aircraft and consists of the following sub-modules:

- Ground
- Strut Forces
- Runway Roughness
- Runway Conditions
- Structural Contact
- Tire Failures

Simulator Motion System

The six degree of freedom motion system provides accelerations that are representative of the aircraft motion. The simulator cockpit is located on top of a motion platform with movement provided by six hydraulic actuators. The actuators are controlled by signals from the motion control cabinet. Because the motion actuators are of limited travel, sustained low frequency accelerations are not possible. The flight accelerations are passed through a complex set of filters to optimize the motion response for important training maneuvers such as takeoffs, aborted takeoffs, and landings.

The motion system receives the following inputs from the simulator host software:

- Aircraft flight model accelerations

- Special effects not generated in the aircraft flight model but injected to enhance the realism of the simulation (concrete slab joints, touchdown bump, gear extension/retraction bumps, wind gust cues, etc.)
- Buffet (higher order vibrations) associated with specific aircraft maneuvers.

Existing B737 Simulator Surface Roughness Models

The B737-800 simulator provides a generic surface roughness model with selectable intensity levels from 0 to 5. The main roughness model consists of the following components:

Mat and spall bumps - The model generates vertical deviations in the ground surface to simulate small depressions and holes (spalls) and larger patched areas (mats). A random function generates the deviations independently for each landing gear. The vertical deviations are input first into the tire and strut model, flow into the ground and flight models with resulting aircraft accelerations then sent from the host computer to the motion system.

Surface roughness vibrations - The higher order vibrations associated with surface roughness are modeled on a spectral analysis of real world aircraft vibrations associated with taxiing at 30 knots on a rough runway. The amplitude of the vibrations is modulated with respect to the simulator ground speed and the selected intensity level. The higher order vibration commands are input to the motion system where frequency generators are used to produce the higher frequency vibrations.

NEW SURFACE ROUGHNESS MODEL

A new surface roughness model was developed to provide simulator motion response to real-world airport surface elevation profiles. The roughness model was developed in two stages. Initially, the surface elevation profiles were input into the existing rigid body flight model. Next, simulation of the aircraft flexible body reaction to the surface roughness was added.

Surface Elevation Profiles

Surface elevation profiles provide elevation data from actual airport runways and taxiways. The profiles depict airport surface elevation changes in feet along the longitudinal axis of the airport runway or taxiway. The elevation profiles are two-dimensional; height varies only with respect to x-distance along the pavement.

Profile sample spacing was chosen to keep the data files within size constraints and still provide realistic simulator response. The B737-800 simulator flight model runs at a rate of sixty times per second. The highest ground speed for a 737-800 is approximately 150 knots or 250 feet per second. At this speed, the flight model will respond to a change in surface elevation every 4.16 feet (250fps / 60sec). A surface profile sample spacing of four feet was chosen based on the simulator response rate at the highest anticipated ground speed. The elevations between these points are determined by linear interpolation. Taxiway profiles with one-foot spacing were also tested at taxiway speeds later in the study.

The elevation profiles are formatted as follows for use on the flight simulator:

- Each profile is stored as an ASCII data file.
- Elevation height is represented in feet to match the simulator ground model format.
- Profiles are two-dimensional; height varies along surface length and is uniform across the width of the surface.
- Four-foot sample spacing was chosen to provide a balance between data file size and resolution.
- Very low frequency variations in elevation were removed by high-pass filtering at a cutoff wavelength of 1,000 ft (304.8 m).

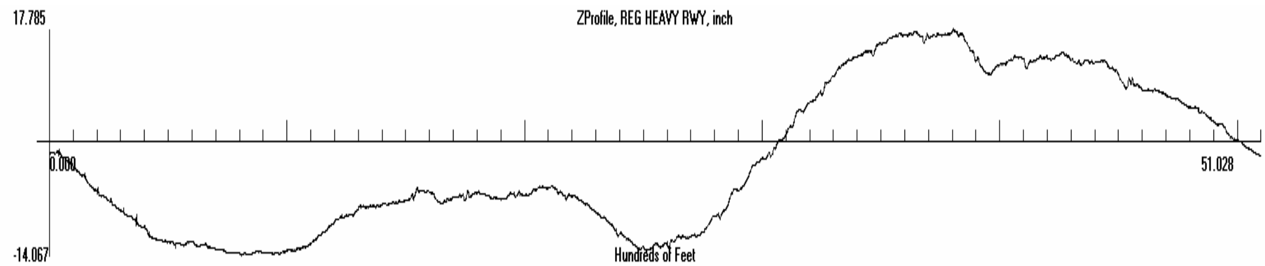

Figure 2. Example runway elevation profile before high-pass filtering.

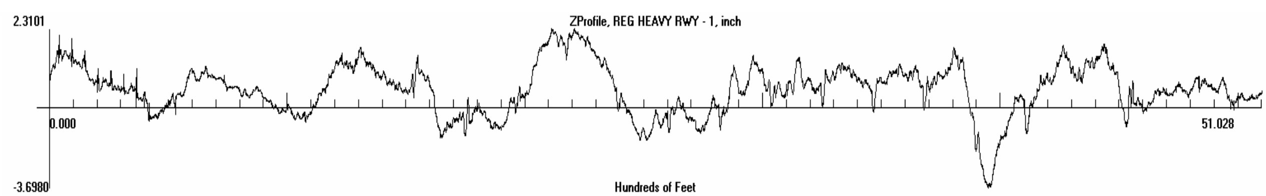

Figure 3. Example runway elevation profile after high-pass filtering.

The following test profiles were also created for testing the performance of the roughness model during development:

20ft 2" Sine - 10 Periods
40ft 2" Sine - 10 Periods
80ft 2" Sine - 10 Periods
200ft 2" Raised Cosine Bump
200ft 2" Lowered Cosine Dip
200ft 4" Raised Cosine Bump
200ft 4" Lowered Cosine Dip
400ft 4" Raised Cosine Bump
400ft 4" Lowered Cosine Dip
20ft 2" Raised Cosine Bump

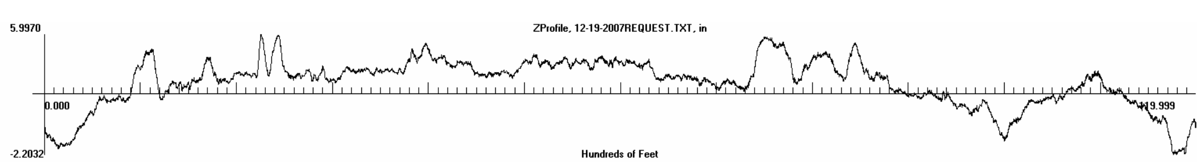

Figure 4. Electronic runway profile at 4-ft spacing prepared for input to the simulator roughness model.

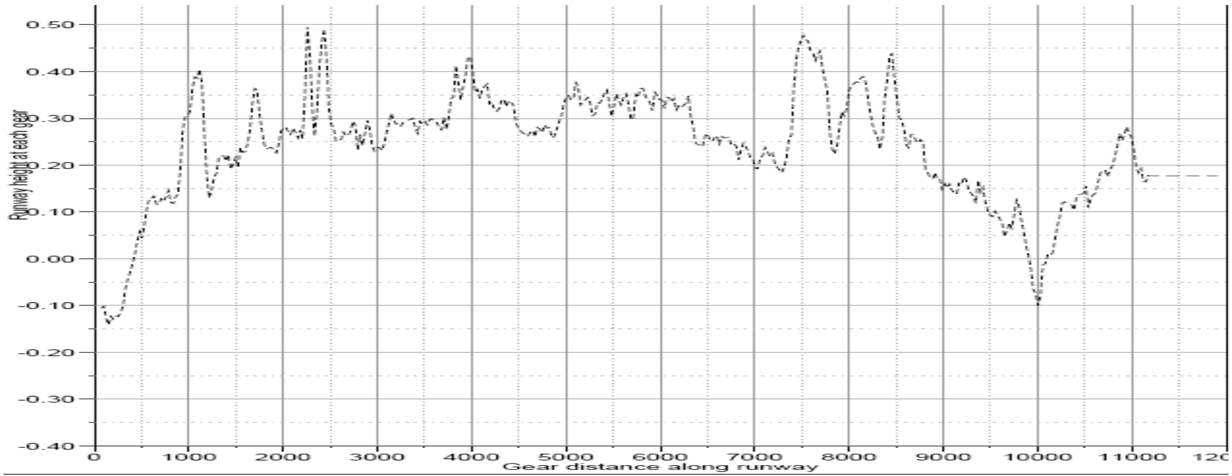

Figure 5. Runway height at the left main gear downloaded from the simulator roughness model as the simulation model passed down the runway. Generated after input of the profile in figure 4.

Integration of Surface Profiles into the Simulator Flight Model

Software was developed for modeling the aircraft interaction with surface roughness profiles and to allow profile selection, control, and testing. The use of roughness profile data files facilitates the transfer of real-world aircraft data into the simulator and provides the ability to easily change the selection of roughness profiles.

A control page at the simulator instructor station provides the user interface for selection and control of the surface roughness profiles and for disabling the existing roughness models. Upon selection of an elevation profile, the corresponding data file is read into an array in the simulator flight program.

The selected roughness profile is mapped to the flight simulator reposition runway with the profile starting point aligned with the selected runway's threshold. The existing flight software models the interaction of each landing gear with the ground. The surface profile elevation data is input into the flight model with individual gear height modeled as a function of the gear's position along the elevation profile. First the aircraft center of gravity (CG) x-position along the elevation profile is calculated. Next, each gear's x-position is calculated based on the gear's angle and distance relative to the aircraft CG, and the aircraft heading with respect to the runway heading. These calculations provide realistic surface height inputs to each landing gear as the aircraft moves along the surface.

The strut model generates the gear forces which flow into the flight model equations of motion. The equations of motion generate linear and rotational velocities and accelerations at the aircraft center of gravity.

Addition of Aircraft Flexible Body Modes

The bending mode model added to the simulator software uses strut force as input to excite the bending mode accelerations. The model outputs translational bending mode positions, velocities, and accelerations at five modal positions:

1. Nose Gear
2. Left Main Gear
3. Right Main Gear
4. Center of Gravity (CG)
5. Cockpit

The flexible mode model was implemented in the simulator flight software. Modeling of up to four bending modes was provided, with the number of active bending modes selectable from the instructor station. Code was also added to calculate the predicted cockpit vertical acceleration (GCP) using the following formula:

GCP = (VWGD - VQD * VXXM(1) + ModePosZAccel(5)) / 32.2

Where:

VWGD	=	Z-body acceleration [ft/sec**2]
VQD	=	Pitch acceleration body axis [rad/sec**2]
VXXM(1)	=	X-body distance of nose gear from CG [ft]
ModePosZAccel(5)	=	Flex mode vertical acceleration at cockpit [ft/sec**2]

Initial testing of the flexible mode resulted in unwanted oscillations in the flight accelerations which proved difficult to resolve. The oscillation problem was solved by adding the flexible mode accelerations to the motion system instead of introducing them into the flight model.

Linear, Flexible, Body Dynamics

The airplane is assumed to behave as a lightly damped linearly flexible continuous body, with the response to pavement disturbances being motion of the airframe in the Oz direction relative to a rigid body representation of the unloaded airframe (see figure 6). The assumption of linearity means that the response can be decomposed into its normal modes and each mode treated separately as a single degree of freedom excited by the main and nose gear forces. The total response is then found by summing the responses due to each of the modes. Reference 2 describes this mode summation procedure in general terms and references 3 and 4 describe the procedure as it is typically applied to determine aircraft response to pavement roughness.

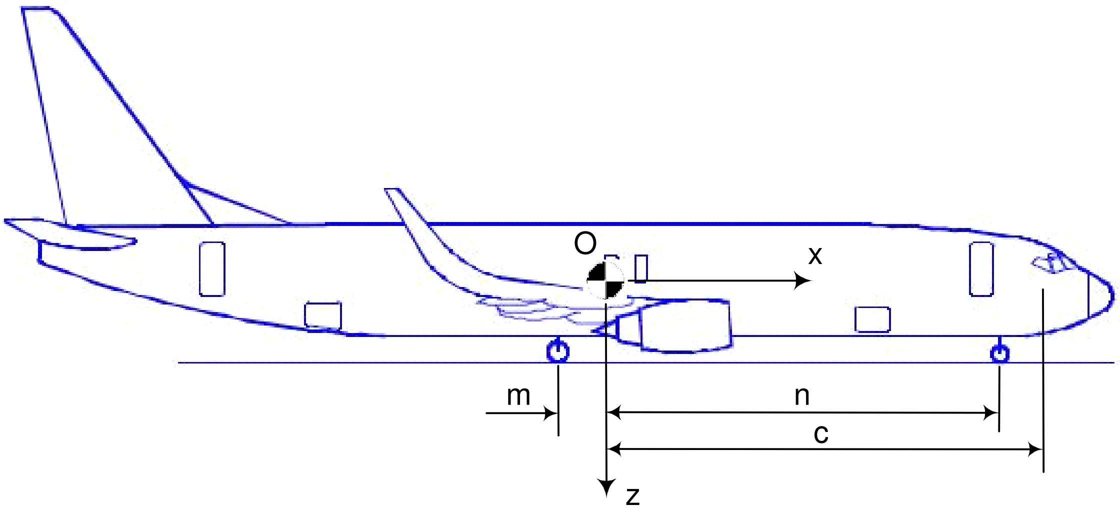

Figure 6. Principal axes and dimensions in the airplane model.

Ox, Oz = orthogonal axes fixed in the airframe rigid body
z_M = vertical displacement of the airframe due to flexible motion at the main gear position relative to *Ox* and in the *Oz* direction
z_N = vertical displacement of the airframe due to flexible motion at the nose gear position relative to *Ox* and in the *Oz* direction
z_C = vertical displacement of the airframe due to flexible motion at the cockpit pilot station relative to *Ox* and in the *Oz* direction

The total flexible vertical response at any position along the airframe is written as:

$$z(x,t) = \sum_{i=1}^{N} q_i(t).\phi_i(x)$$

Where:
$z(x,t)$ = total flexible vertical response at position x along the airframe and time t
$q_i(t)$ = magnitude of the generalized coordinate for mode i
$\varphi_i(x)$ = magnitude of the mode shape for mode i at position x along the airframe

Considering only one mode,

$$z_i(x,t) = q_i(t).\phi_i(x)$$

The undamped equation of motion for mode i with main gear vertical force and nose gear vertical force acting on the airframe is (see reference 2, equation 11.3-4):

$$m_i\ddot{q}_i + k_i q_i = Z_M(t).\phi_i(m) + Z_N(t).\phi_i(n), \text{ or}$$
$$\ddot{q}_i + \omega_i^2 q_i = \frac{1}{m_i}\left(Z_M(t).\phi_i(m) + Z_N(t).\phi_i(n)\right)$$
$$\ddot{q}_i = \frac{1}{m_i}\left(Z_M(t).\phi_i(m) + Z_N(t).\phi_i(n)\right) - \omega_i^2 q_i$$

Where:

m_i = generalized (modal) mass of mode i
k_i = generalized (modal) stiffness of mode i
$Z_M(t)$ = main gear vertical force acting on the airframe
$Z_N(t)$ = nose gear vertical force acting on the airframe
ω_i^2 = natural frequency of mode i (modal frequency of mode i)

The following equations are then integrated numerically for all flexible modes included in the simulation:

$$\dot{q}_i = \int\left(\frac{1}{m_i}\left(Z_M(t).\phi_i(m) + Z_N(t).\phi_i(n)\right) - \omega_i^2 q_i\right).dt$$
$$q_i = \int \dot{q}_i.dt$$

and the main gear and nose gear motions calculated from:

$$z_M(t) = \sum_{i=1}^{N} q_i(t).\phi_i(m), \quad \dot{z}_M(t) = \sum_{i=1}^{N} \dot{q}_i(t).\phi_i(m)$$
$$z_N(t) = \sum_{i=1}^{N} q_i(t).\phi_i(n), \quad \dot{z}_N(t) = \sum_{i=1}^{N} \dot{q}_i(t).\phi_i(n)$$

As described later, the cockpit acceleration due to flexible motion has to be computed in the host computer of the simulator (which is used to run the ground simulation computations) and transferred to the motion computer (which is used to drive the simulator actuators). The cockpit acceleration is computed in the host computer directly from the generalized accelerations at each time step in the simulation:

$$\ddot{z}_C(t) = \sum_{i=1}^{N} \ddot{q}_i(t).\phi_i(c)$$

Parameter values required to simulate the flexible modes are the modal frequencies and modal masses, and the magnitudes of the mode shapes at the main gear, nose gear, and cockpit positions. It has not been possible to obtain values for these parameters from the aircraft manufacturer, so the parameter values for a 727 published in reference 4 have been used. It is not felt that this deficiency in accurately modeling the response of the 737-800 will have a material effect on the pilot's subjective response study because the most important characteristic of the modeling for this project is to be able to introduce higher frequency cockpit motions which are reproducible from run to run in response to specific disturbances in a particular pavement profile. A small amount of linear damping is added to the generalized mode equations to control transient motion resulting from discrete disturbances. The damping factor is currently set at 2.5 percent for all modes. This small amount of damping is unlikely to introduce a noticeable amount of cross coupling between the modes.

Figures 7 and 8 show the effect on cockpit acceleration of adding four flexible modes.

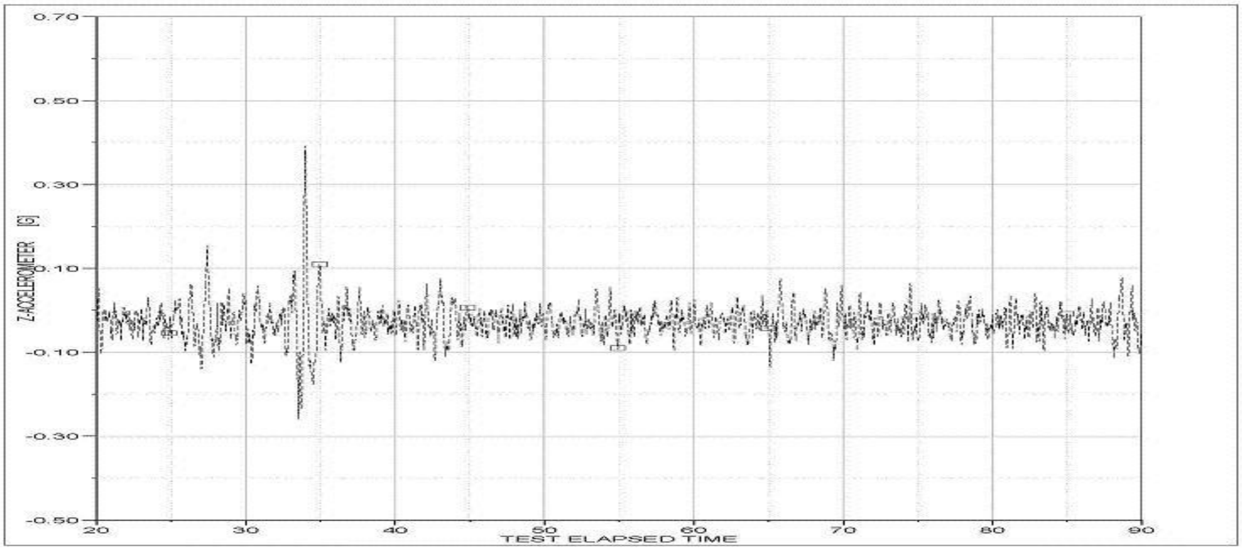

Figure 7. Cockpit vertical accelerations with rigid body modes only.

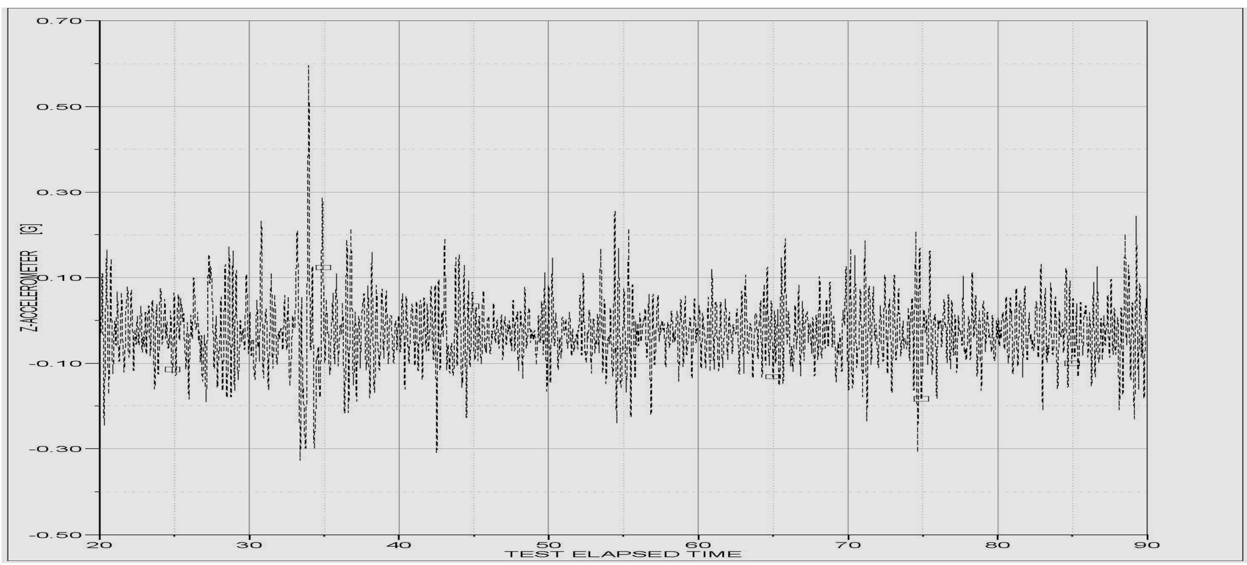

Figure 8. Cockpit vertical accelerations with rigid body modes and 4 flexible modes.

Transfer of Accelerations to the Motion System

The simulator flight model transfers only the CG (not cockpit) accelerations to the motion system. The motion software transforms the CG accelerations into cockpit accelerations. In order to send the cockpit flexible mode data to the motion system, the cockpit vertical accelerations were first translated into pitch accelerations at the CG, and then added to the flight model rigid body pitch velocity and acceleration outputs.

The motion computer is assumed to accept the quantities $\ddot{z}_{cg}$ and $\dot{p}_{tr}$ and to compute the vertical acceleration of the cockpit with the equation:

$$\ddot{z}_{cp} = \ddot{z}_{cg} - x_{cp} \times \dot{p}_{tr}$$

Where:
$\ddot{z}_{cp}$ = vertical cockpit acceleration computed in the motion computer
$\ddot{z}_{cg}$ = vertical acceleration at the cg computed in the host and transferred to the motion computer
$\dot{p}_{tr}$ = pitch acceleration computed in the host and transferred to the motion computer
x_{cp} = distance from the cg to the cockpit in the body OX axis direction

The desired result in the motion computer is:

$$\begin{aligned}\ddot{z}_{cp} &= \ddot{z}_{cg} - \dot{p} \times x_{cp} + \ddot{z}_{fmcp} \\ &= \ddot{z}_{cg} - x_{cp}\left(\dot{p} - \frac{\ddot{z}_{fmcp}}{x_{cp}}\right)\end{aligned}$$

Where:
$\dot{p}$ = rigid body pitch acceleration computed in the host computer
$\ddot{z}_{fmcp}$ = cockpit vertical acceleration due to all flexible modes computed in the host computer

Therefore, the pitch acceleration which needs to be computed in the host computer and transferred to the motion computer is:

$$\dot{p}_{tr} = \dot{p} - \frac{\ddot{z}_{fmcp}}{x_{cp}}$$

Acceleration at the cg, $\ddot{z}_{cg}$, is the rigid body acceleration computed in the host computer. The flexible modes acceleration does not need to be added before transfer to the motion computer.

Motion Filter Tuning

The motion system filters the flight model accelerations in order to optimize the motion response within its limited motion range. The filters are tuned to enhance the realism of maneuvers critical for flight training such as takeoff rotation, aborted takeoffs, and deceleration after touchdown. High pass filters are used to limit low frequency motions and maintain the motion actuators near their mid range. It was possible to enhance the cockpit vertical response to surface roughness by adjusting the vertical high pass filter. The normal settings for the vertical high pass filter are a breakpoint of 2.5 rad/s (0.4 Hz) with a gain of 0.7. The break frequency was decreased to 0.1 rad/s (0.016 Hz) and the gain increased to 1.0. This adjustment increased the cockpit vertical acceleration response to surface roughness profiles by approximately 30 percent. However, changing the filter settings severely degraded the realism of the simulator motion during maneuvers such as rotation in a takeoff and braking after landing. The filter settings were therefore left as standard during further testing.

SURFACE ROUGHNESS MODEL EVALUATION

Test Procedures

Tests were developed to evaluate the roughness model performance through the collection of time histories for the following parameters:

Runway x-distance of main gear
Runway height at nose gear
Runway height at main gear
Equivalent airspeed
Number of bending modes modeled
Bending mode airframe damping
Bending mode Z acceleration at cockpit
Gear vertical forces
Pitch velocity
Pitch acceleration
Bending mode rigid body pitch velocity
Bending mode rigid body pitch acceleration
Computed cockpit vertical acceleration
Cockpit vertical accelerometer

Roughness profile tests were performed to assess the effect of ground speed on cockpit accelerations. The following time histories show the accelerations measured below the pilot's seat in the cockpit for test runs on the runway profile shown in figures 4 and 5 at speeds of 50, 100, and 130 knots. Speed was held constant along the full length of the runway during each of the runs.

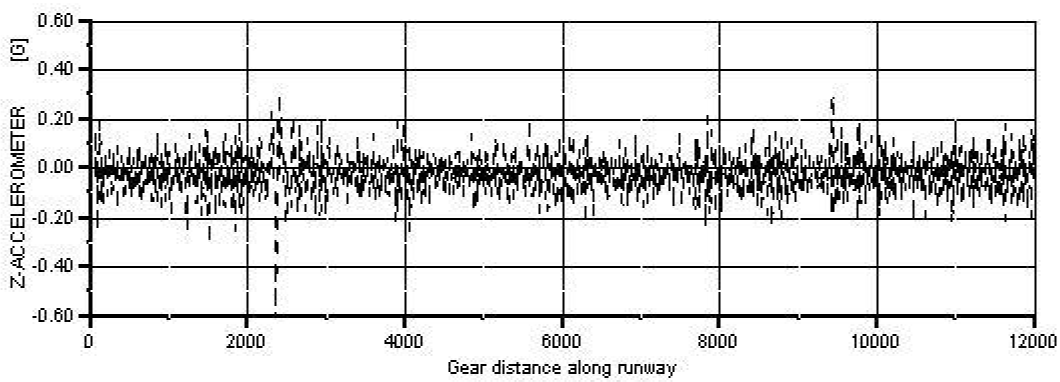

Figure 9. Cockpit vertical acceleration - 50 knots.

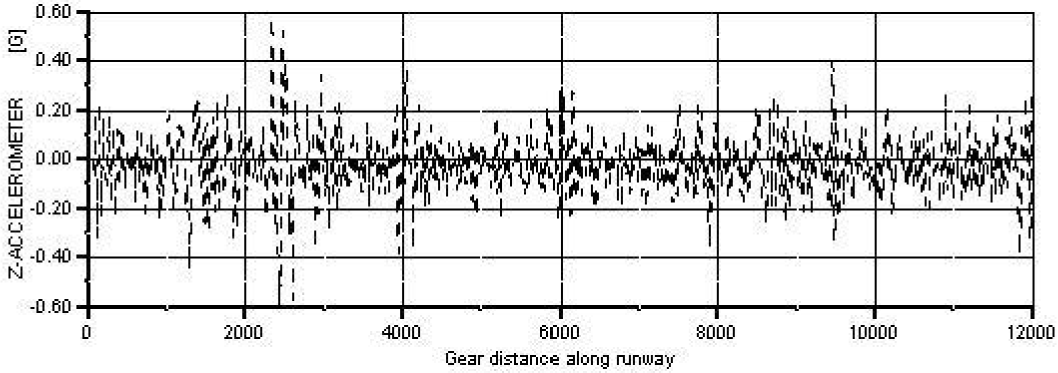

Figure 10. Cockpit vertical acceleration - 100 knots.

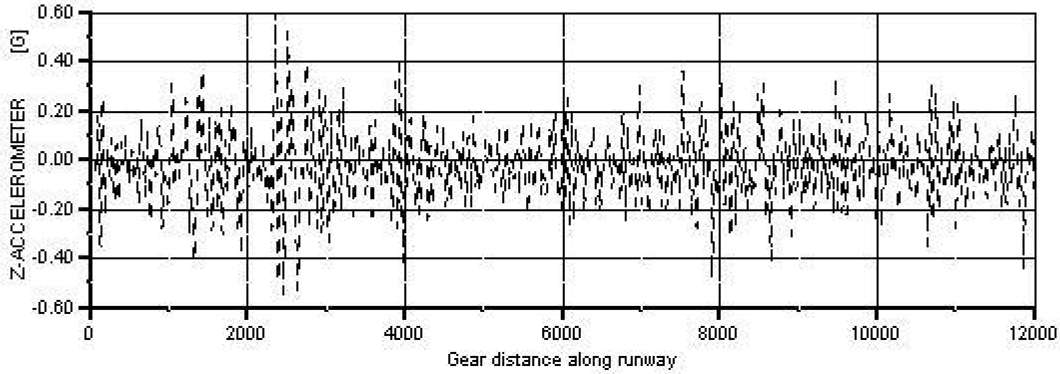

Figure 11. Cockpit vertical acceleration - 130 knots

Subjective Pilot Evaluation

The B737 surface roughness model was demonstrated to commercial airline industry pilots to obtain their feedback on the model's realism. The pilots were asked to perform taxiing, takeoffs, aborted takeoffs, and landings with various runway roughness models and to provide feedback on the experience. The following roughness models were used for this demonstration:

- Generic runway roughness at levels 1, 3, and 5
- A fairly rough runway profile measured at an international airport.
- A very rough runway profile measured at a regional airport.
- A very smooth runway profile measured at a regional airport.
- A fairly rough taxiway profile measured at a regional airport.

Overall the pilot's feedback indicated that the profile roughness models provided a realistic simulation of real world runways with the following exceptions:

- Cockpit response to runway centerline lights was missing despite the presence of visual cues from the display.

- Cockpit response to concrete section joint bumps was missing despite the presence of visual cues.
- Background tire rumble was missing.

CONCLUSIONS

A B737-800 simulator surface roughness model was successfully implemented allowing input of real world surface profiles and providing realistic cockpit motion response to the profile elevation changes. The surface roughness model provided a distinct enhancement over the existing runway roughness models through the use of selectable real world surface profiles which provided a greater range of roughness variability and intensity.

The addition of aircraft flexible modes to the roughness model greatly enhanced the cockpit acceleration response to roughness by providing the higher frequency vibrations resulting from aircraft travel on rough surfaces.

Motion filter tuning increased the intensity of the cockpit motion response, but greatly reduced the realism of maneuvers such as takeoffs and landings. The filter tuning effects were especially noticeable during rotation on takeoff and braking after landing. The possible addition of centerline light bumps, concrete joint sections, and background tire rumble will be explored in the next phase of this project.

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